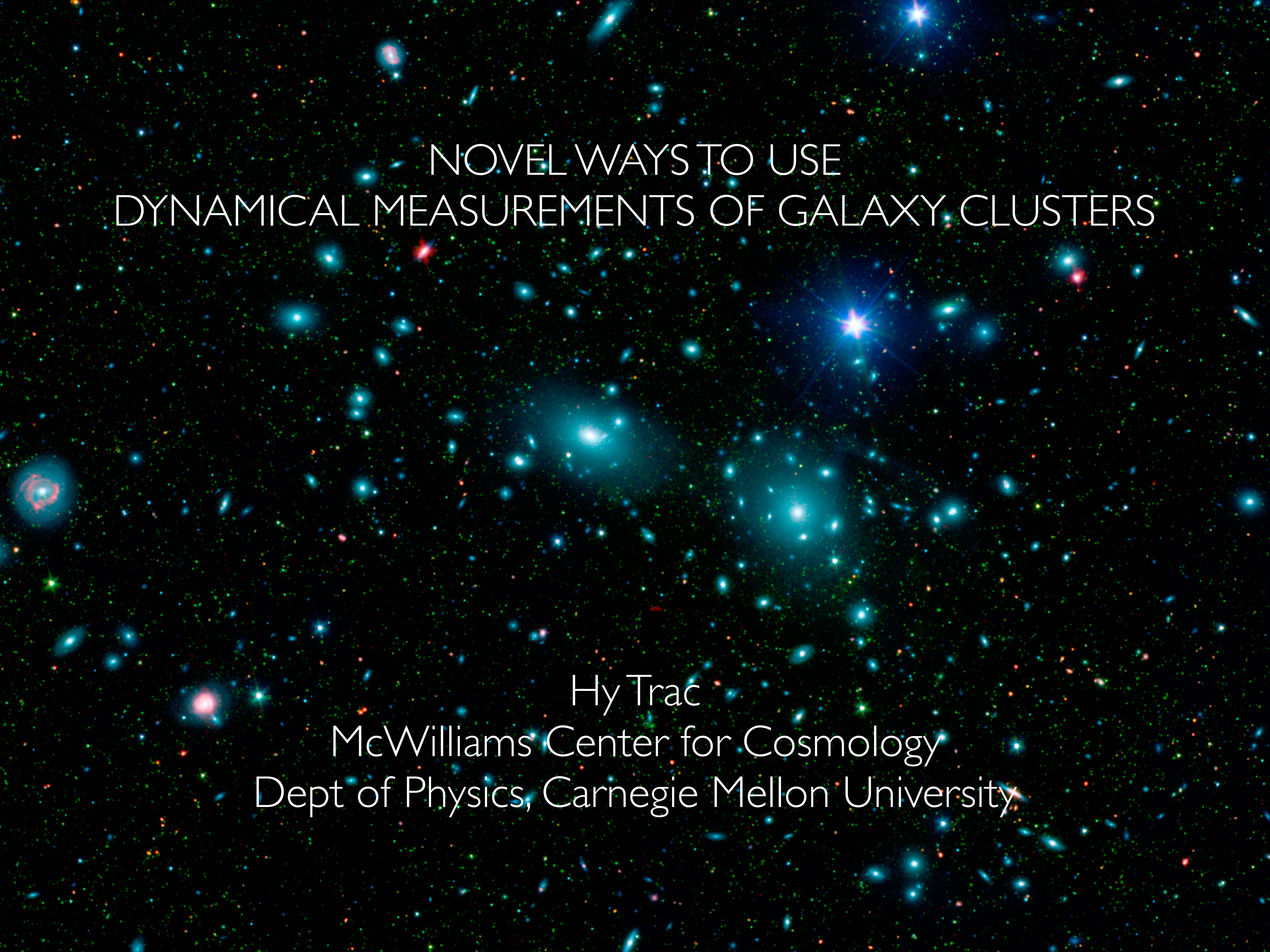

NOVEL WAYS TO USE DYNAMICAL MEASUREMENTS OF GALAXY CLUSTERS

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COSMOLOGY, MACHINE LEARNING, ASTROSTATISTICS

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GALAXY CLUSTERS ARE SHY ABOUT THEIR MASS

Richness
Dynamics
Caustics
Lensing
Sunyaev-Zel'dovich
X-ray

ZWICKY 1933, 1937

Die Rotverschiebung von extragalaktischen Nebeln

von F. Zwicky.

(16. II. 33.)

Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merkmale extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung derselben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalaktischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklärung dieses wichtigen Phänomens aufgestellt worden sind, werden kurz besprochen. Schliesslich wird angedeutet, inwiefern die Rotverschiebung für das Studium der durchdringenden Strahlung von Wichtigkeit zu werden verspricht.

§ 1. Einleitung.

Es ist schon seit langer Zeit bekannt, dass es im Weltraum gewisse Objekte gibt, welche, wenn mit kleinen Teleskopen beobachtet, als stark verschwommene, selbstleuchtende Flecke erscheinen. Diese Objekte besitzen verschiedenartige Strukturen. Oft sind sie kugelförmig, oft elliptisch, und viele unter ihnen haben ein spiralartiges Aussehen, weshalb man sie gelegentlich als Spiralnebel bezeichnet. Dank des enormen Auflösungsvermögens der modernen Riesenteleskope gelang es, festzustellen, dass diese Nebel ausserhalb der Grenzen unseres eigenen Milchstrassensystems liegen. Aufnahmen, die mit dem Hundert-Zoll-Teleskop auf dem Mt. Wilson gemacht worden sind, offenbaren, dass diese Nebel Sternsysteme sind, ähnlich unserem eigenen Milchstrassensystem. Die extragalaktischen Nebel sind im grossen und ganzen gleichförmig über den Himmel und, wie gezeigt werden konnte, auch gleichförmig über den Weltraum verteilt. Sie treten als einzelne Individuen auf oder gruppieren sich zu Haufen. Die folgenden Zeilen beabsichtigen einen kurzen Abriss der wichtigeren Merkmale und eine Beschreibung der Methoden, welche es möglich gemacht haben, diese Merkmale zu fixieren.

§ 2. Entfernungen und allgemeine Merkmale extragalaktischer Nebel.

Wie schon erwähnt, gelingt es, mit Hilfe der modernen Teleskope eine ganze Anzahl von Nebeln ganz oder teilweise in einzelne Sterne aufzulösen. Im grossen Nebel in Andromeda z. B. sind eine grosse Zahl von individuellen Sternen beobachtet worden.

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 86 | OCTOBER 1937 | NUMBER 3

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

ABSTRACT

Present estimates of the masses of nebulae are based on observations of the *luminosities* and *internal rotations* of nebulae. It is shown that both these methods are unreliable; that from the observed luminosities of extragalactic systems only lower limits for the values of their masses can be obtained (sec. i), and that from internal rotations alone no determination of the masses of nebulae is possible (sec. ii). The observed internal motions of nebulae can be understood on the basis of a simple mechanical model, some properties of which are discussed. The essential feature is a central core whose internal *viscosity* due to the gravitational interactions of its component masses is so high as to cause it to rotate like a solid body.

In sections iii, iv, and v three new methods for the determination of nebular masses are discussed, each of which makes use of a different fundamental principle of physics.

Method iii is based on the *virial theorem* of classical mechanics. The application of this theorem to the Coma cluster leads to a minimum value $\overline{M} = 4.5 \times 10^{10} M_\odot$ for the average mass of its member nebulae.

Method iv calls for the observation among nebulae of certain *gravitational lens* effects.

Section v gives a generalization of the principles of ordinary *statistical mechanics* to the whole system of nebulae, which suggests a new and powerful method which ultimately should enable us to determine the masses of all types of nebulae. This method is very flexible and is capable of many modes of application. It is proposed, in particular, to investigate the distribution of nebulae in individual great clusters.

As a first step toward the realization of the proposed program, the Coma cluster of nebulae was photographed with the new 18-inch Schmidt telescope on Mount Palomar. Counts of nebulae brighter than about $m = 16.7$ given in section vi lead to the gratifying result that the distribution of nebulae in the Coma cluster is very similar to the distribution of luminosity in globular nebulae, which, according to Hubble's investigations, coincides closely with the theoretically determined distribution of matter in isothermal gravitational gas spheres. The high central condensation of the Coma cluster, the very gradual decrease of the number of nebulae per unit volume at great distances from its center, and the hitherto unexpected enormous extension of this cluster become here apparent for the first time. These results also suggest that the current classification of nebulae into relatively few *cluster nebulae* and a majority of

DUNKLE MATERIE IN THE COMA CLUSTER

Distance

$d \sim 13.8$ Mpc

$H_0 \sim 500$ km/s/Mpc

Size

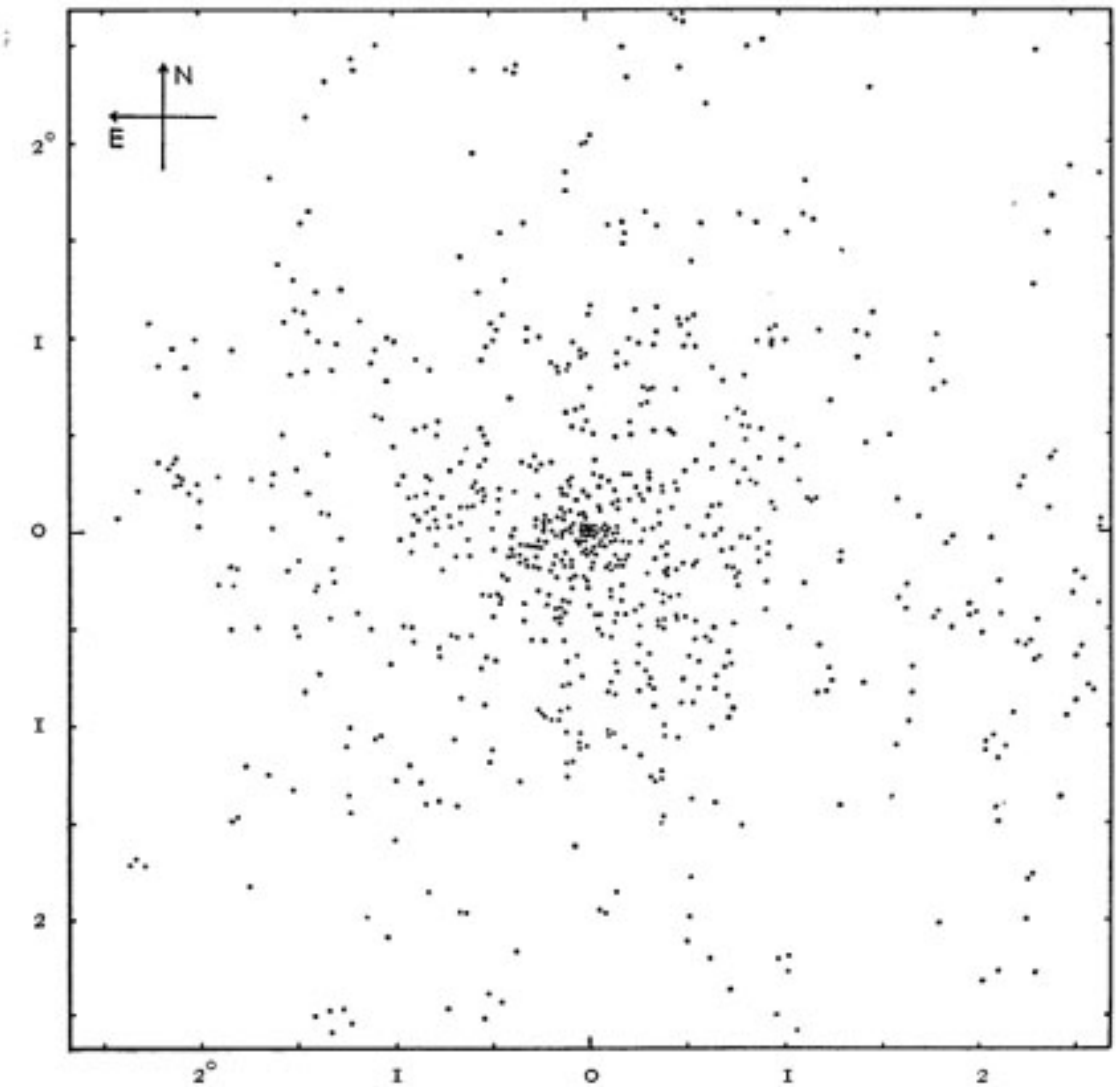
$\theta \sim 0.8$ deg

$R \sim 0.6$ Mpc

Dynamical mass

$\sigma \sim 700$ km/s

$$M_{\rm dyn} \propto \frac{\sigma^2 R}{G} \sim 4.5 \times 10^{13}\ M_\odot$$



(Zwicky 1937)

Mass-to-light ratio of ~500 is much larger than stellar systems

COMA CLUSTER

Redshift and distance

$z \sim 0.023$

$d \sim 100\ \mathrm{Mpc}$

Luminous mass

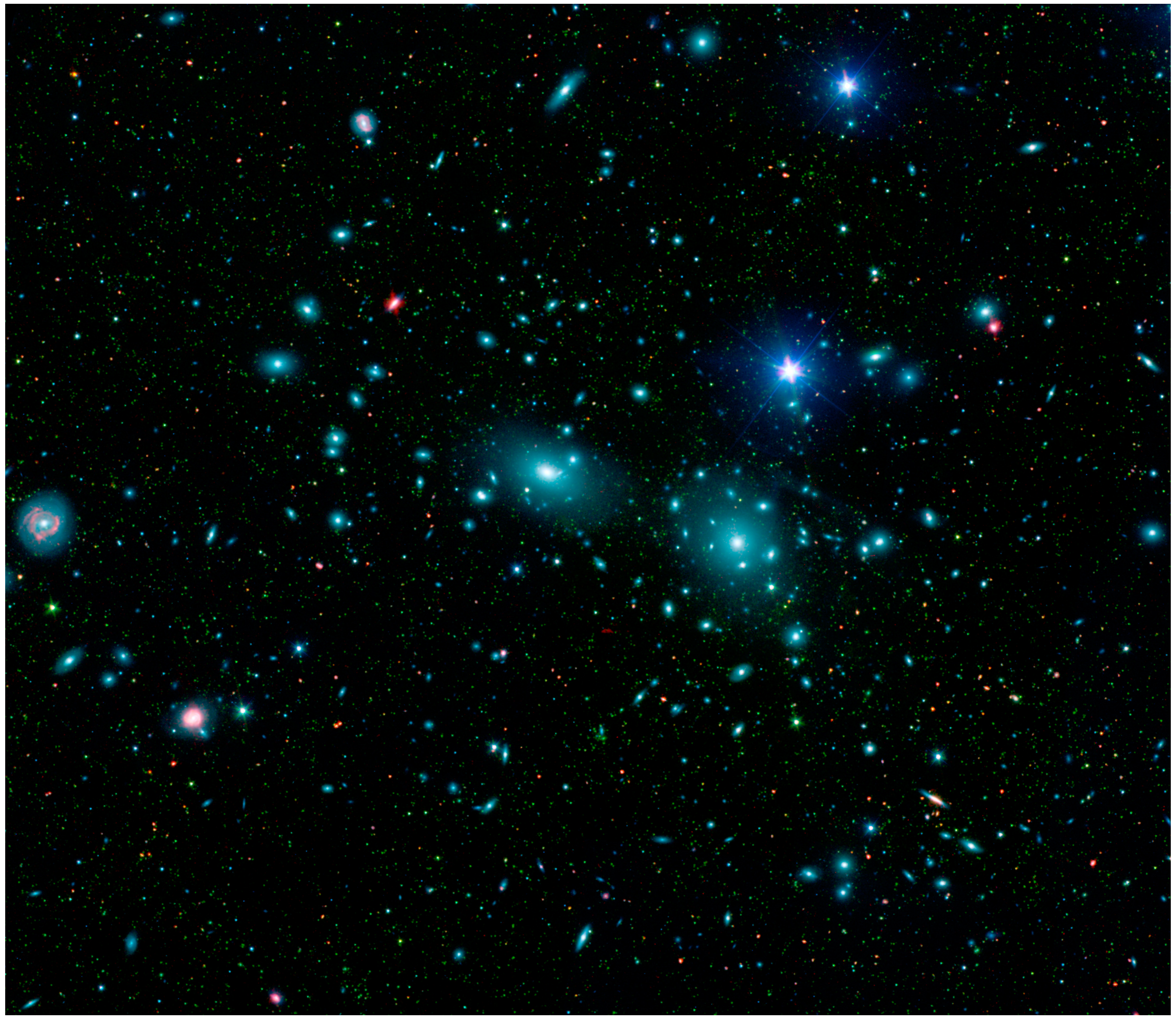
$M_{\mathrm{star}} \sim 3 \times 10^{13}\ M_{\odot}$

$M_{\mathrm{gas}} \sim 2 \times 10^{14}\ M_{\odot}$

Dynamical mass

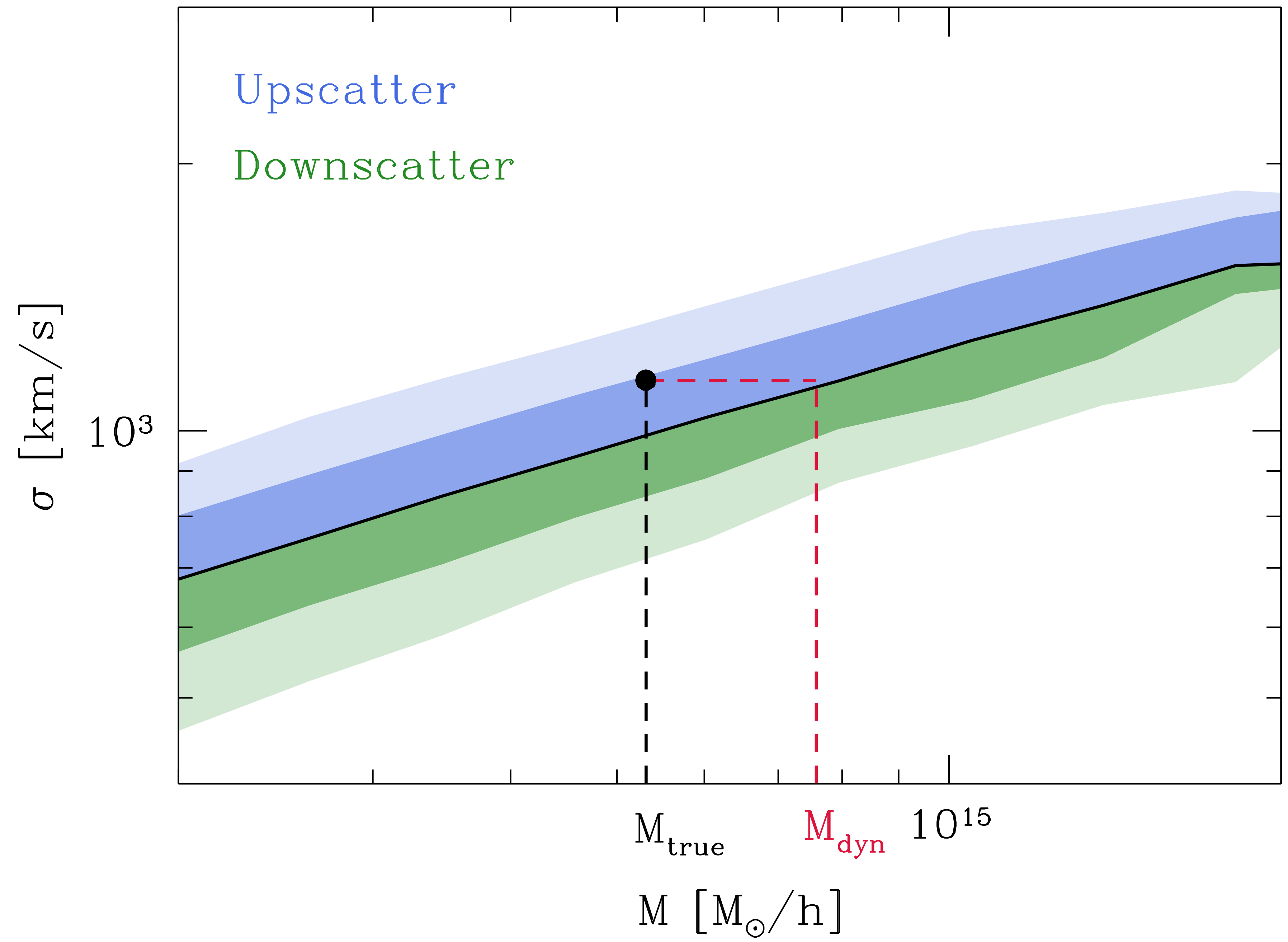
$\sigma \sim 900\ \mathrm{km/s}$

$$M_{\mathrm{dyn}} \propto \frac{\sigma^2 R}{G} \sim 2 \times 10^{15}\ M_{\odot}$$



(SDSS + Spitzer)

DYNAMICAL MASS



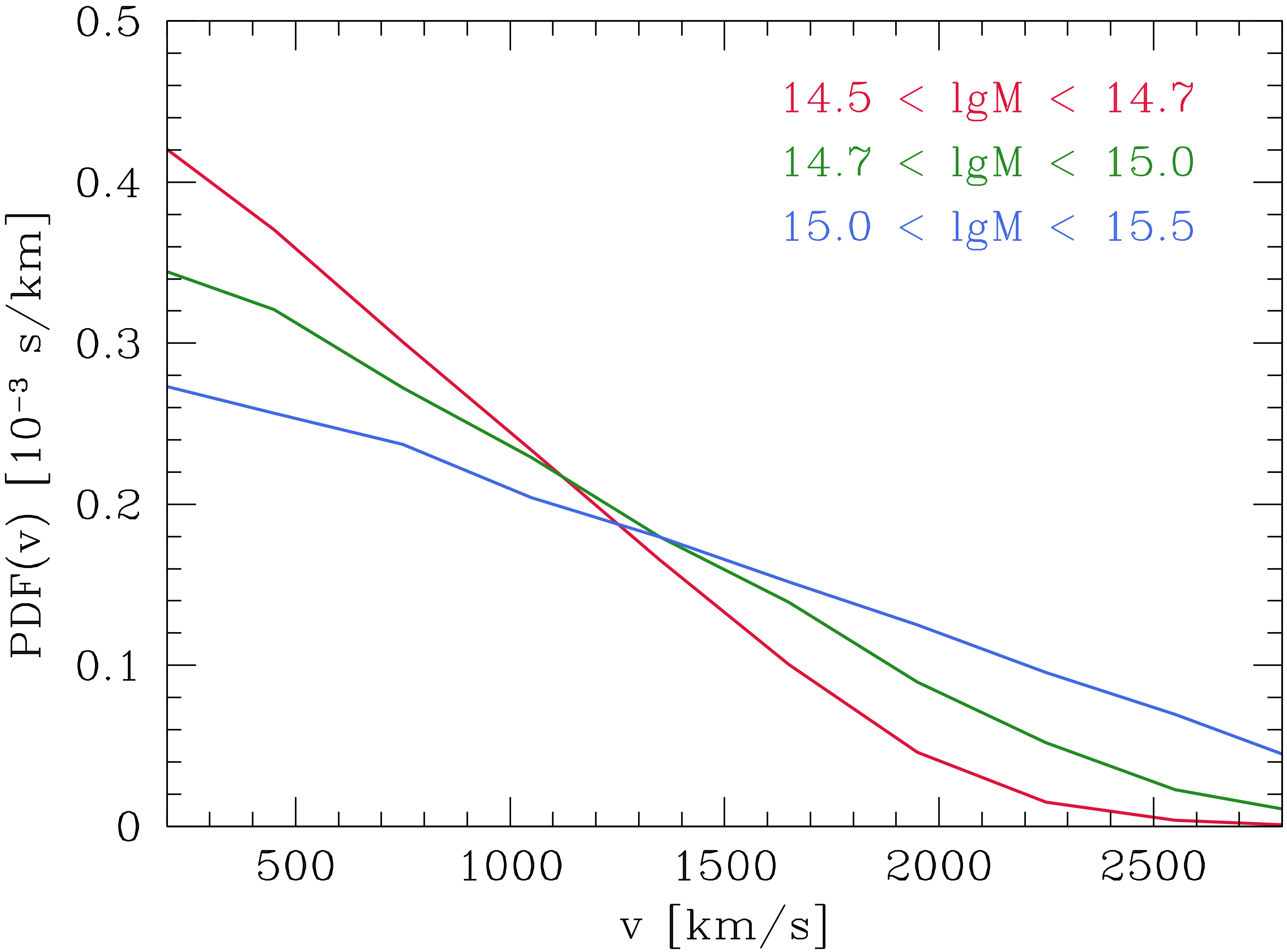
When a scaling relation is used to infer cluster mass from velocity dispersion, the error distribution is broad and has extended high-error tails.

Why should we use velocity dispersion to infer dynamical mass?

Ntampaka, HT, Sutherland, Battaglia, Poczos, & Schneider, A Machine Learning Approach for Dynamical Mass Measurements of Galaxy Clusters, 2015a, ApJ, 803, 50

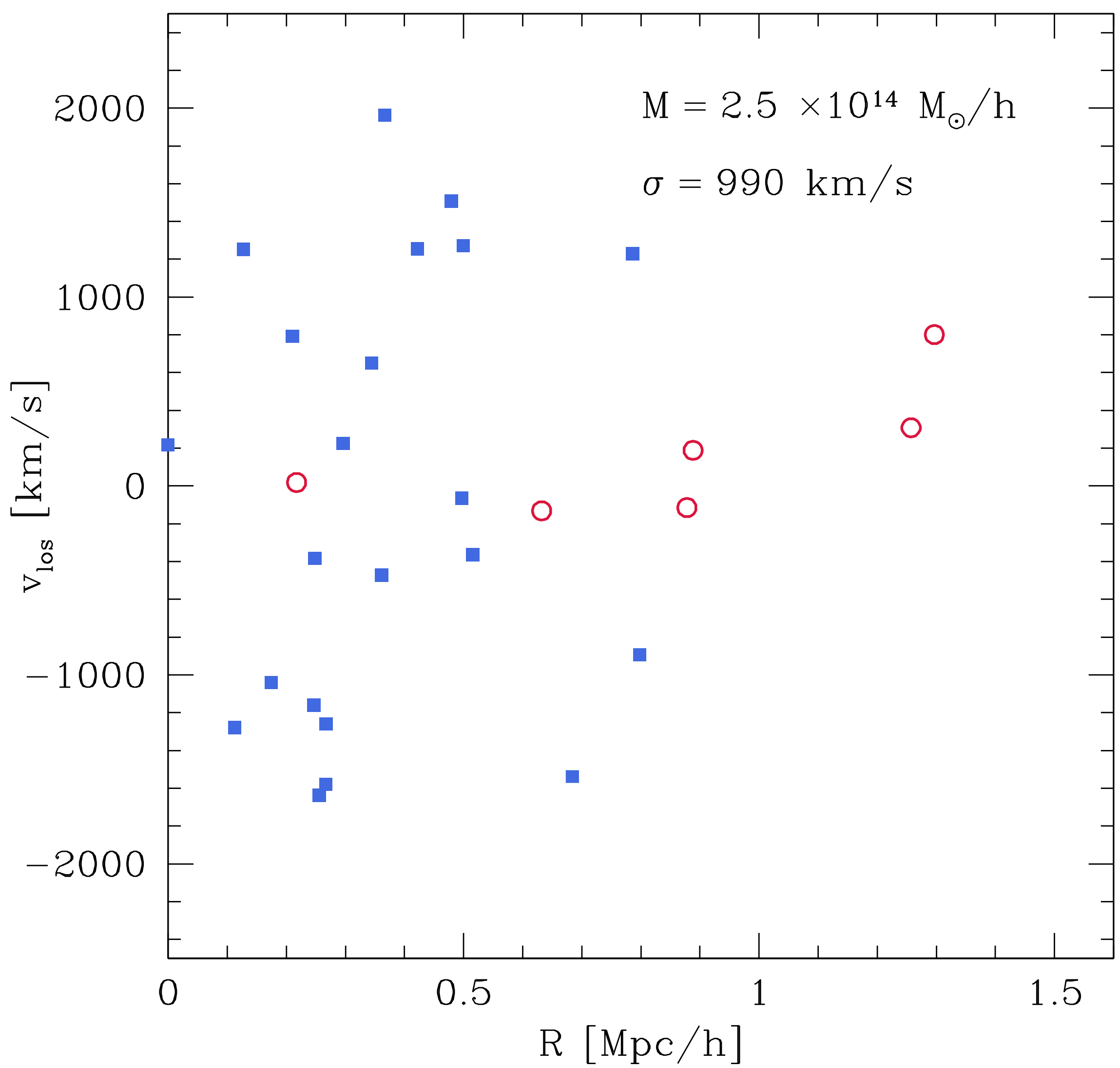
Ntampaka, HT, Sutherland, Fromenteau, Poczos, & Schneider, Dynamical Mass Measurements of Contaminated Galaxy Clusters using Machine Learning, 2015b, ApJ in press, arxiv:1509.05409

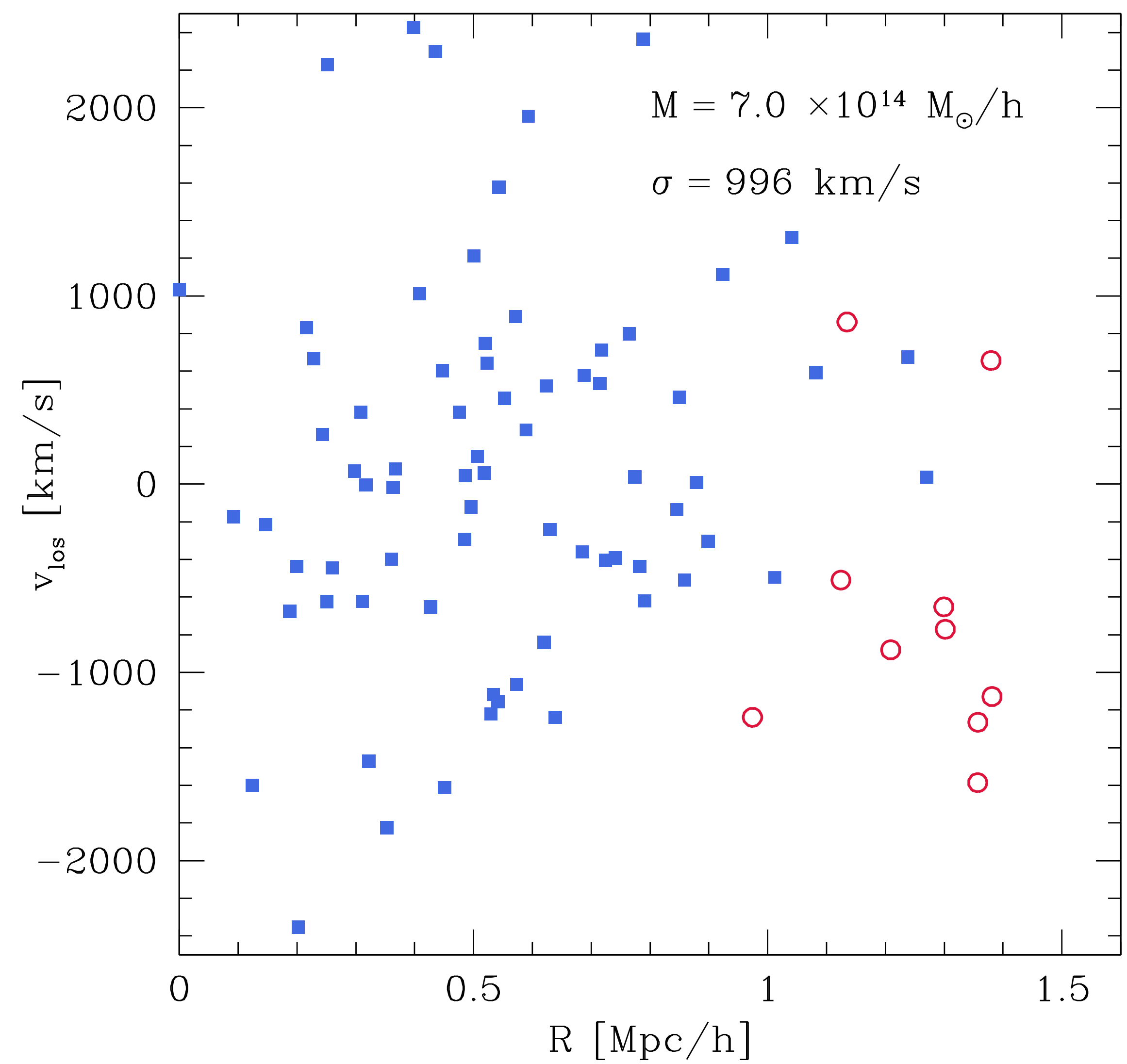
PDF OF GALAXY VELOCITIES



The velocity distribution contains more information about a cluster's mass than simply the velocity dispersion or higher-order moments like skewness and kurtosis.

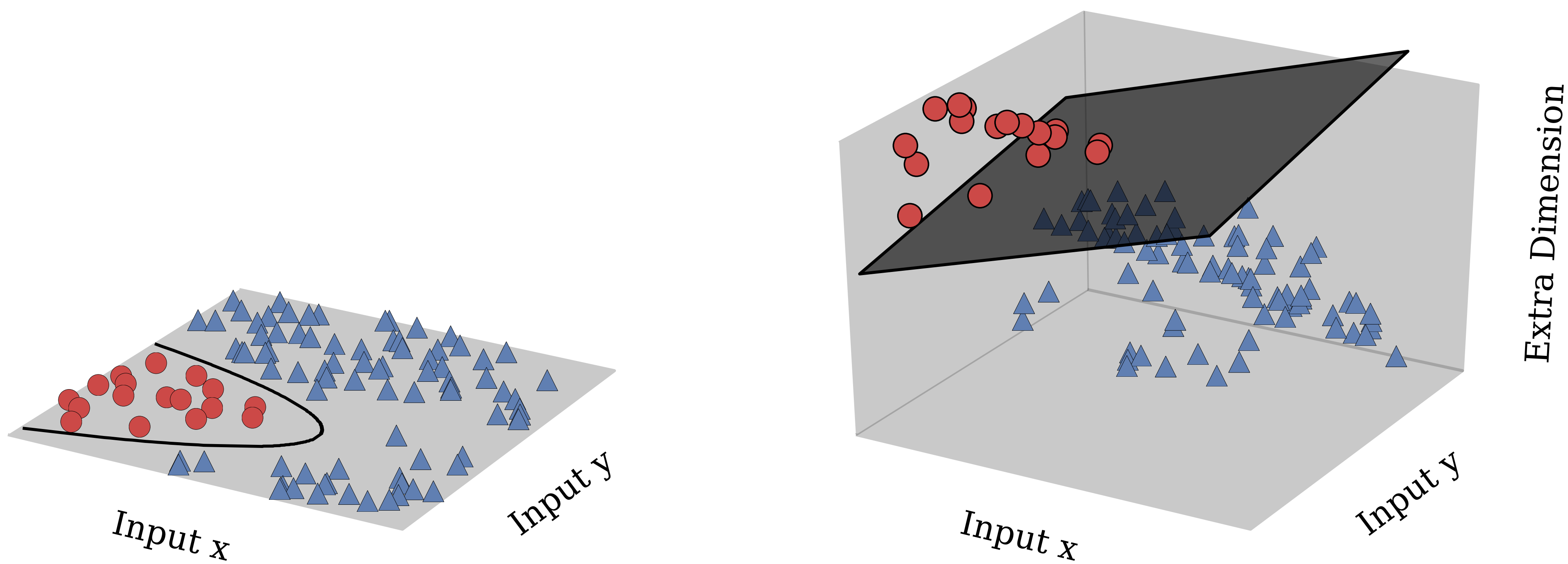
DYNAMICAL PHASE-SPACE





Two clusters with different masses can have similar velocity dispersions (and vice versa).

SUPPORT VECTOR/DISTRIBUTION MACHINES



SVM: train on data vectors, separate objects by decision boundary in feature space, used for classification and regression

SDM: train on distributions, calculate kernel/basis matrix and coefficients analogous to least-squares minimization, regression to predict a scalar (i.e. mass)

Galaxy cluster features: line-of-sight velocities, projected radii, …

MOCK CLUSTER CATALOGS

MultiDark N-body simulation

- $L = 1$ Gpc/h, $N_{dm} = 57$ billion
- $M_{halo} > 10^{14}$ Msolar/h, $M_{subhalo} > 10^{12}$ Msolar/h

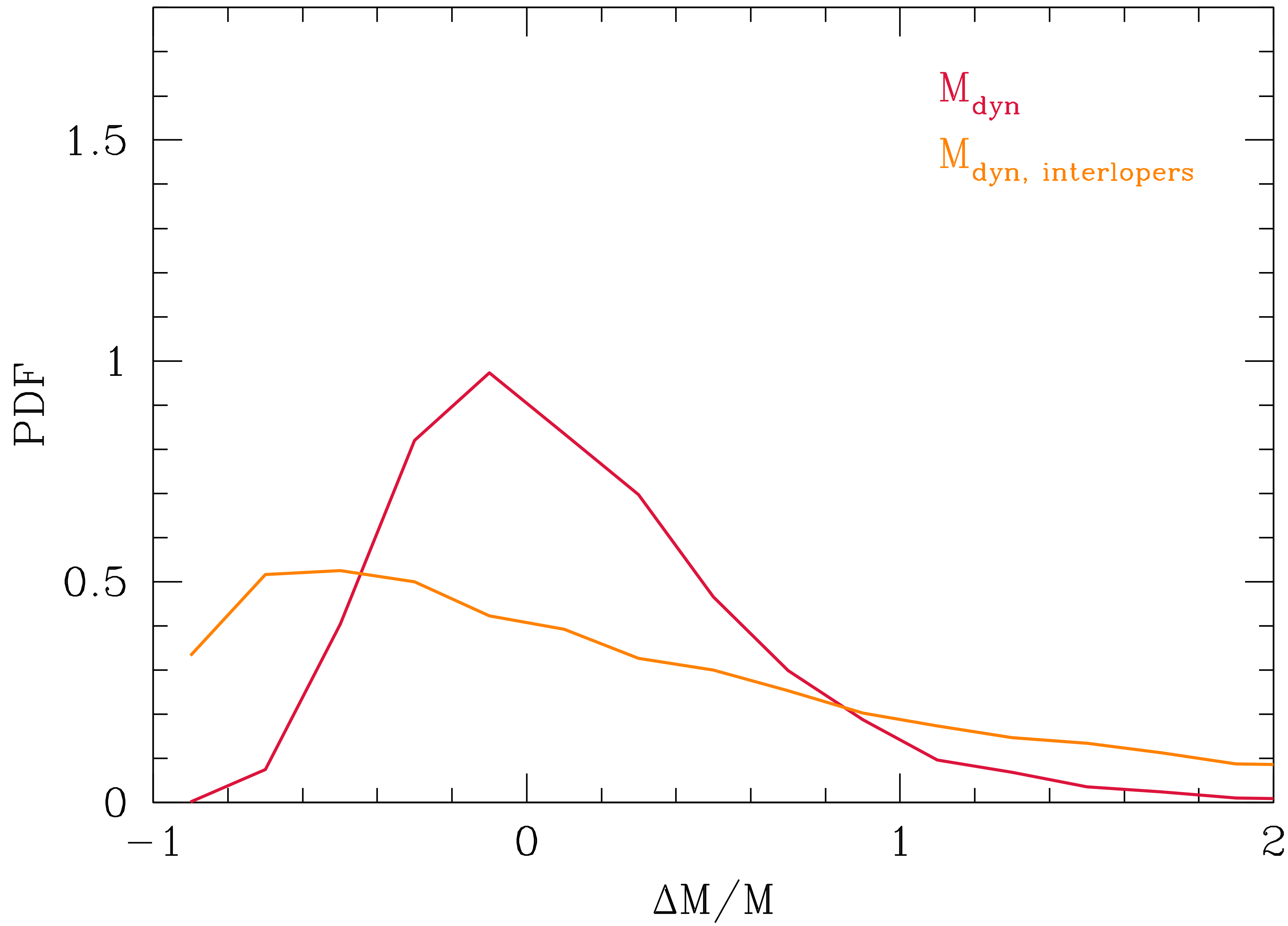
Spherical catalog

- Spherical aperture
- $r < R_{200c}$
- $N_{galaxy} > 20$
- w/o rms errors of 100 km/s
- Pure and complete galaxy membership

Cylindrical catalog

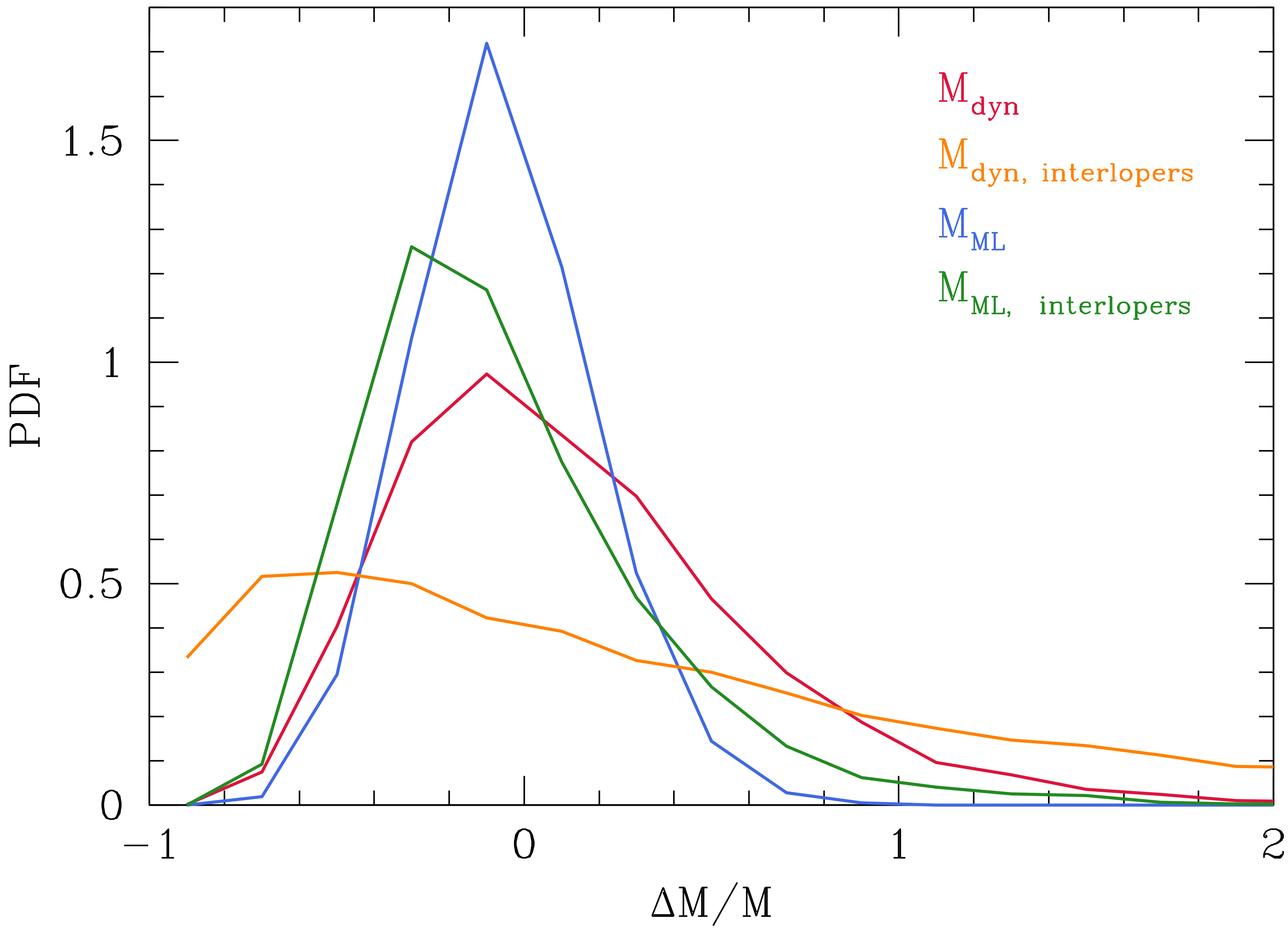
- Cylindrical aperture
- $R < 1.6$ Mpc/h
- $v_{los} < 2500$ km/s
- w/o rms errors of 100 km/s
- Contaminated and incomplete galaxy membership

MASS ERROR DISTRIBUTION



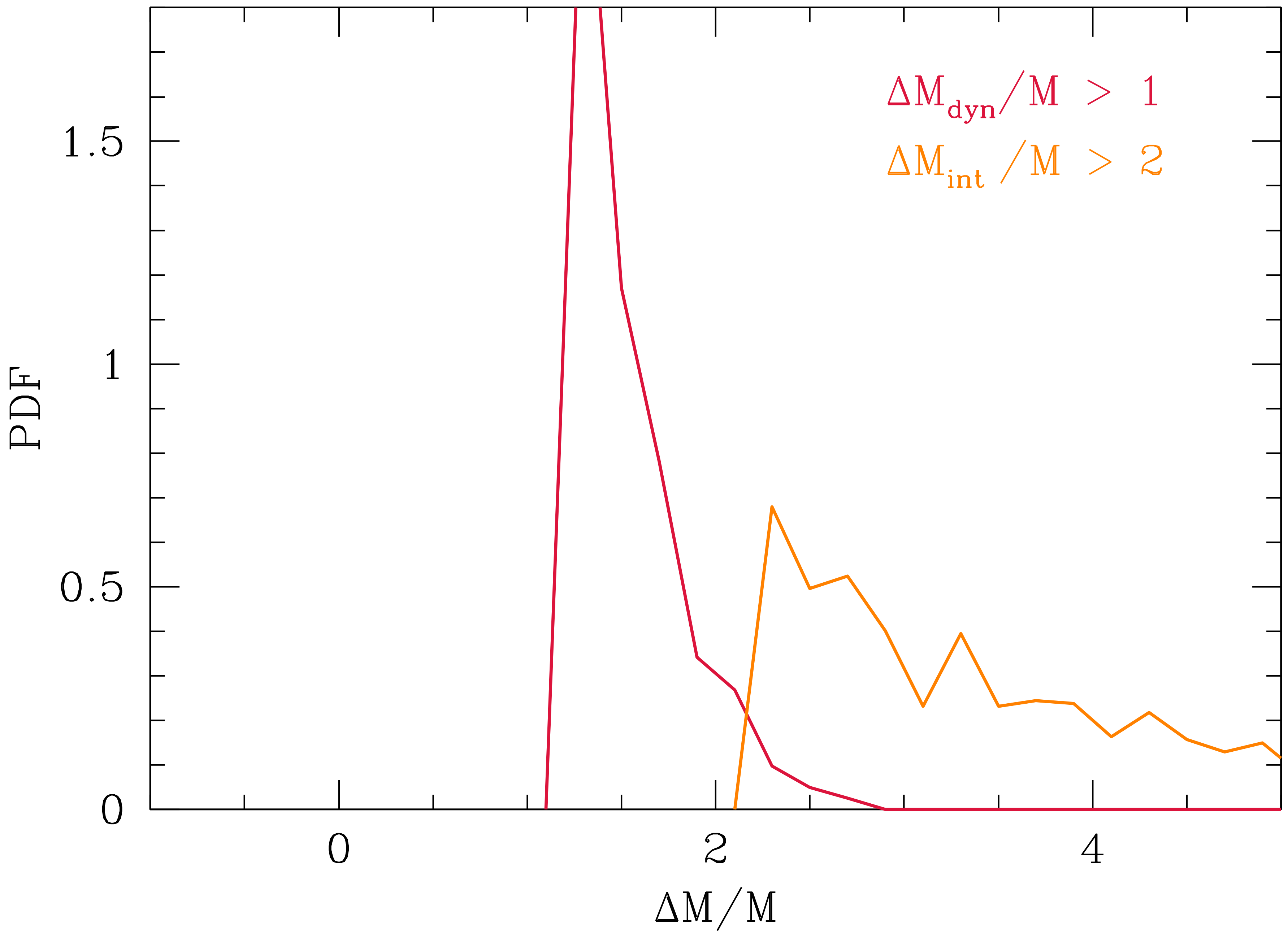
Simple analysis using a powerlaw scaling relation yields a wide fractional mass error distribution.

MASS ERROR DISTRIBUTION



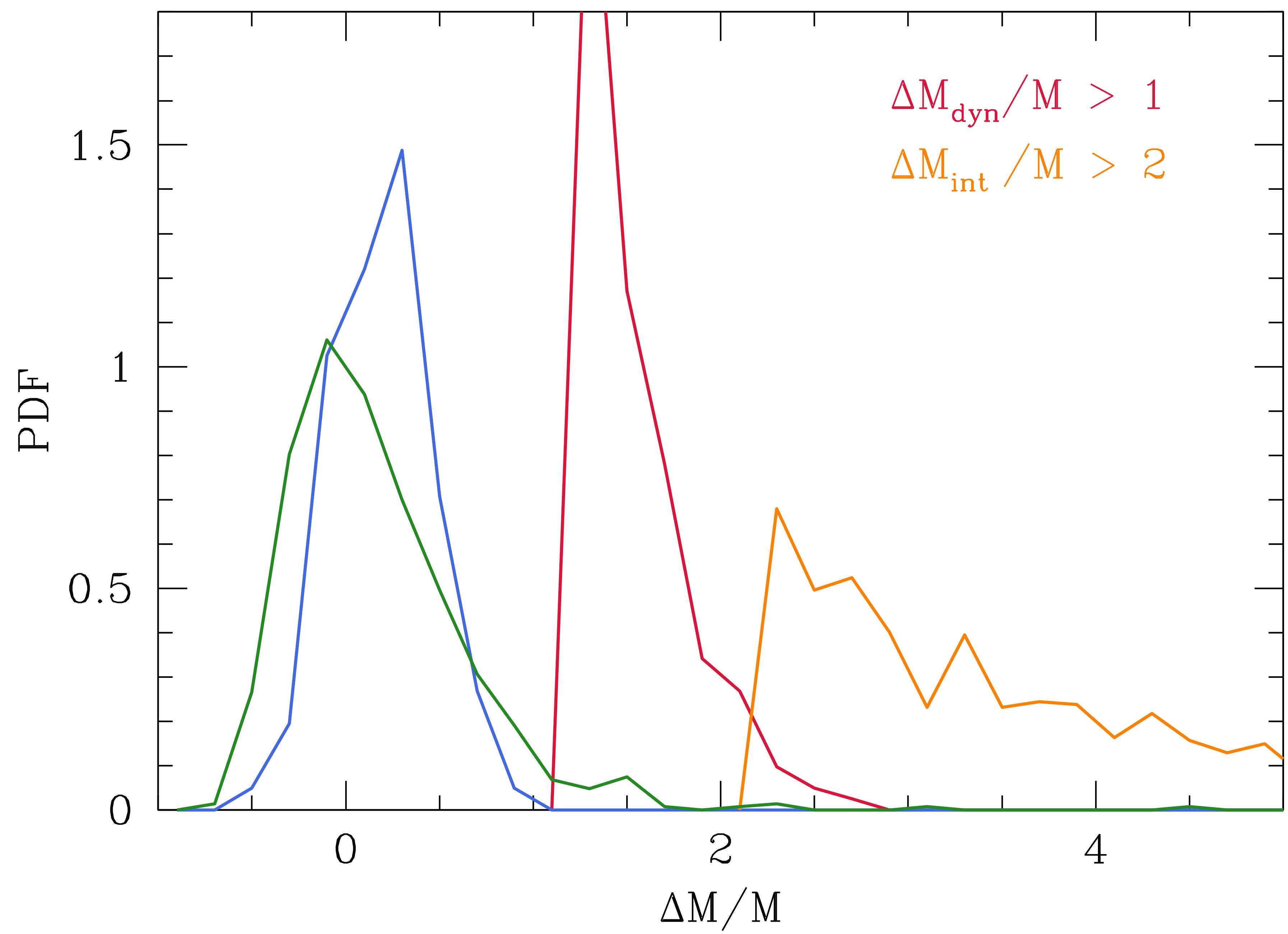
SDM reduces the width of the fractional mass error distribution by a factor of more than 2.

MASS ERROR DISTRIBUTION



Simple analysis using a powerlaw scaling relation yields unwanted high-error tails.

MASS ERROR DISTRIBUTION



SDM effectively eliminates the problematic high-error tail.

ADDITIONAL WORK

Apply machine learning to observed clusters

- e.g. Coma has over 700 galaxies within $R < 2$ Mpc and $|v| < 2500$ km/s
- Chen, Ntampaka, et al in prep

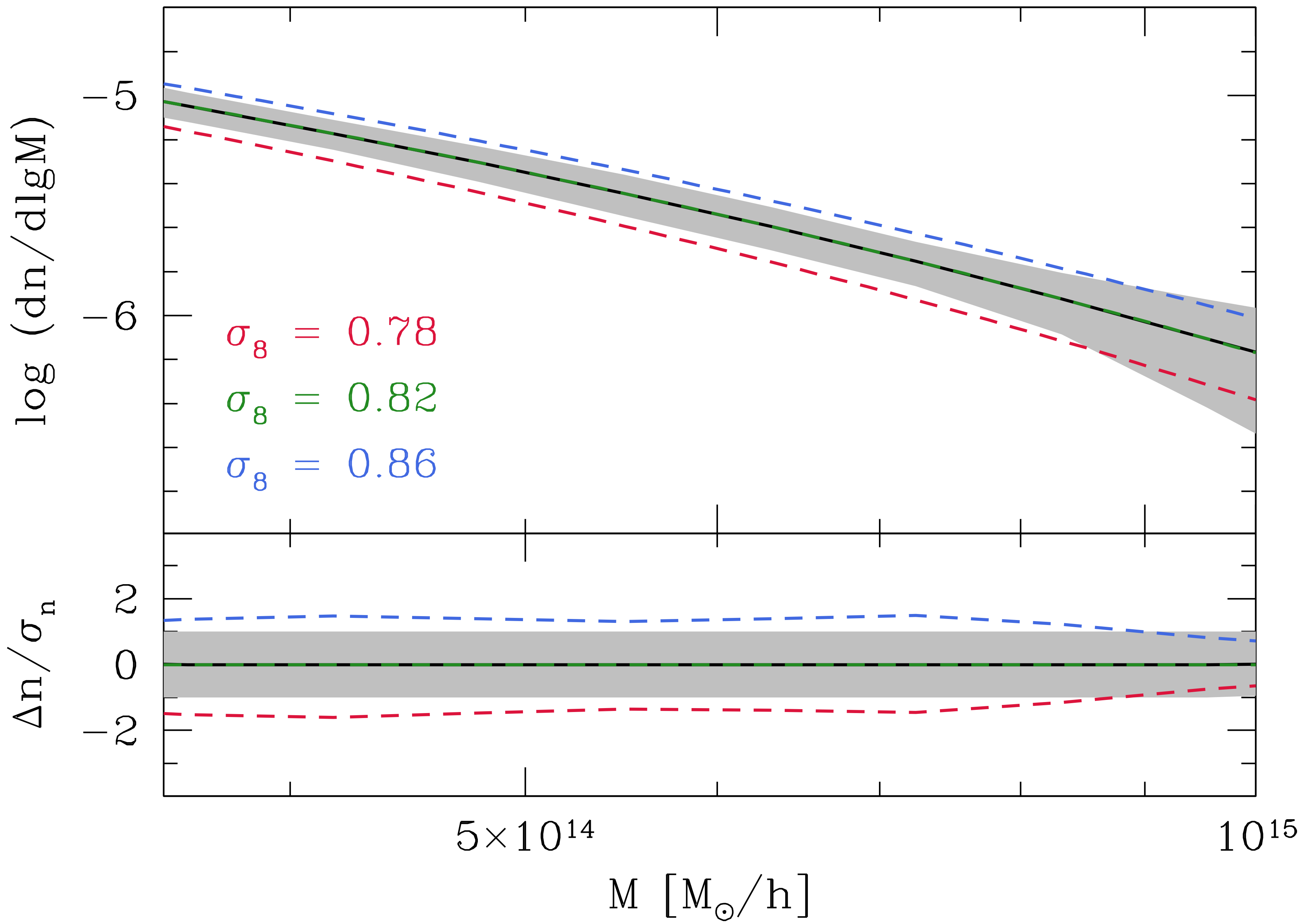
Why should we predict just a mass with machine learning?

- Train on multi-wavelength images e.g. optical, SZ, X-ray
- Predict the corresponding image of the projected mass density

Why should we count clusters as a function of mass?

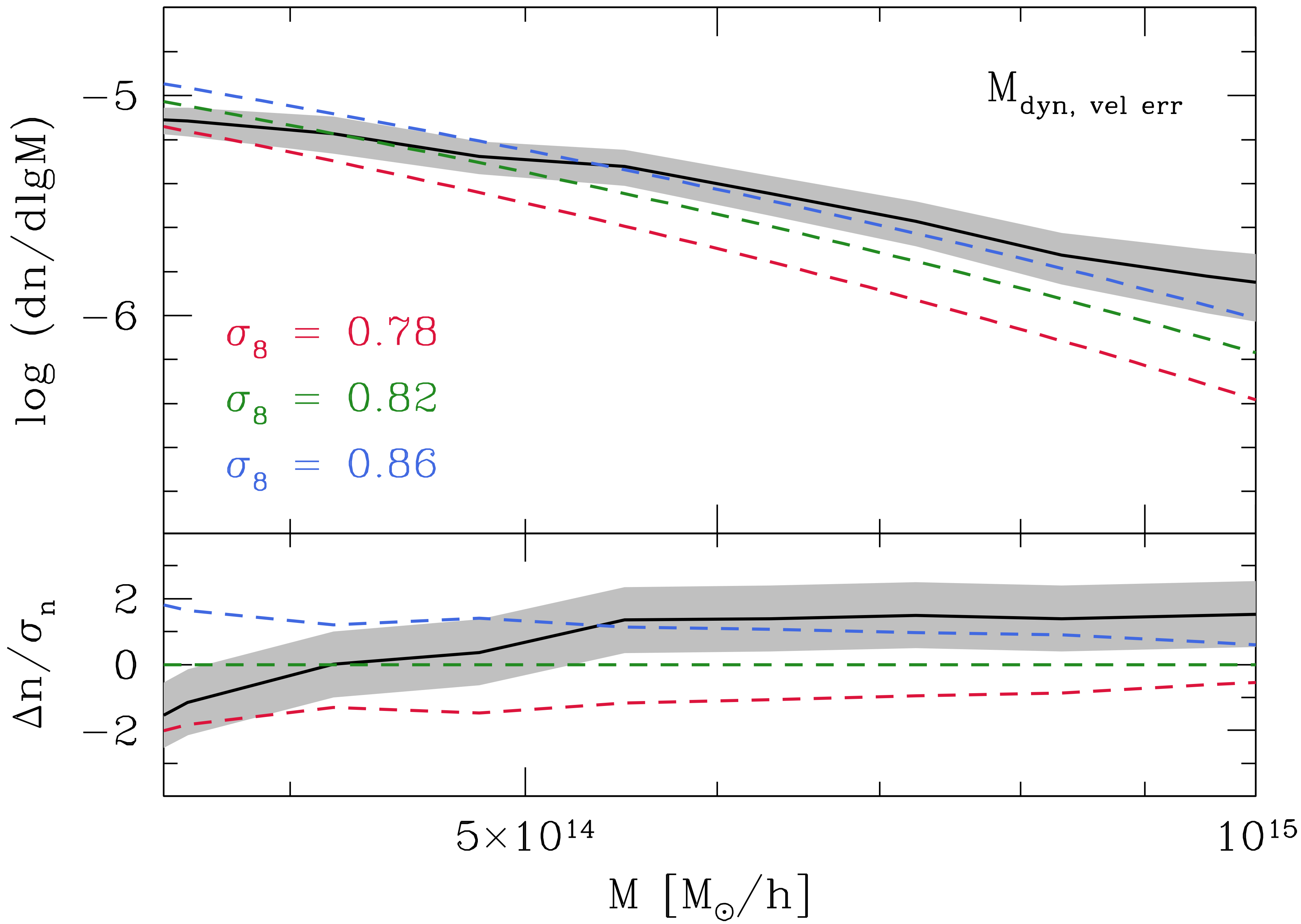
Ntampaka, HT, Cisewski, & Price, The Velocity Distribution Function of Galaxy Clusters as a Cosmological Probe, 2016, submitted to ApJ, arxiv:1602.01837

COUNTING CLUSTERS BY MASS



The halo mass function can be used to measure the dark matter and dark energy mass-energy densities and the normalization of matter perturbations.

COUNTING CLUSTERS BY MASS



The halo mass function quantified using dynamical masses with is significantly biased prior to accounting for Eddington bias.

WHY USE A SINGLE NUMBER TO REPRESENT A CLUSTER?

Halo mass function (HMF)

- Defined as the comoving number density of halos per unit mass
- A given cluster is represented by a single value or a likelihood for mass
- Bin N clusters in a known volume V

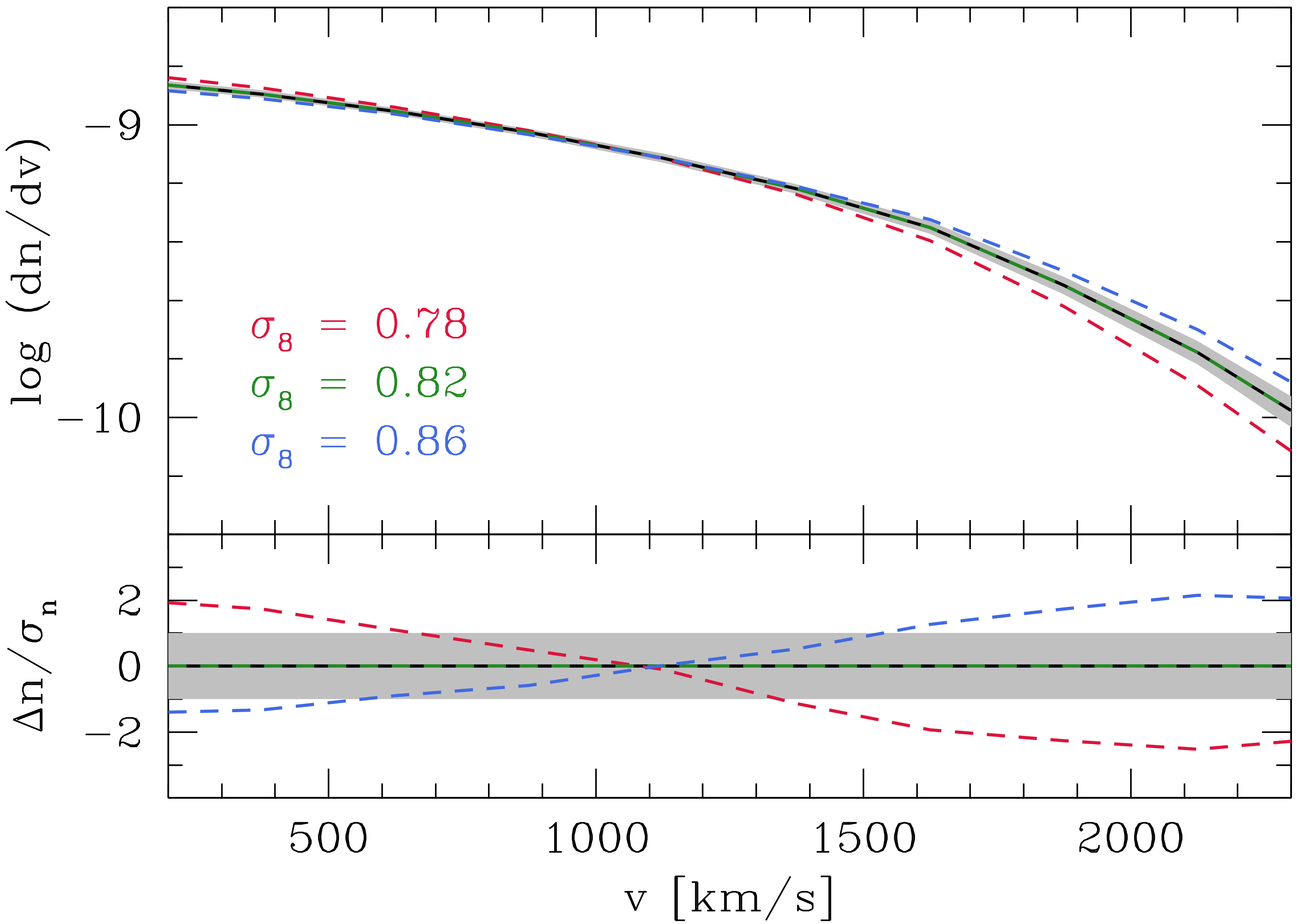
$$\frac{dn}{dM}(M) = \frac{1}{V}\sum_{i}^{N}[\mathrm{PDF}(M)]_i$$

Velocity distribution function (VDF)

- Defined as the comoving number density of halos per unit velocity/speed
- A given cluster is represented by the PDF of galaxy velocities/speed
- Stack N ranked clusters in a known volume V

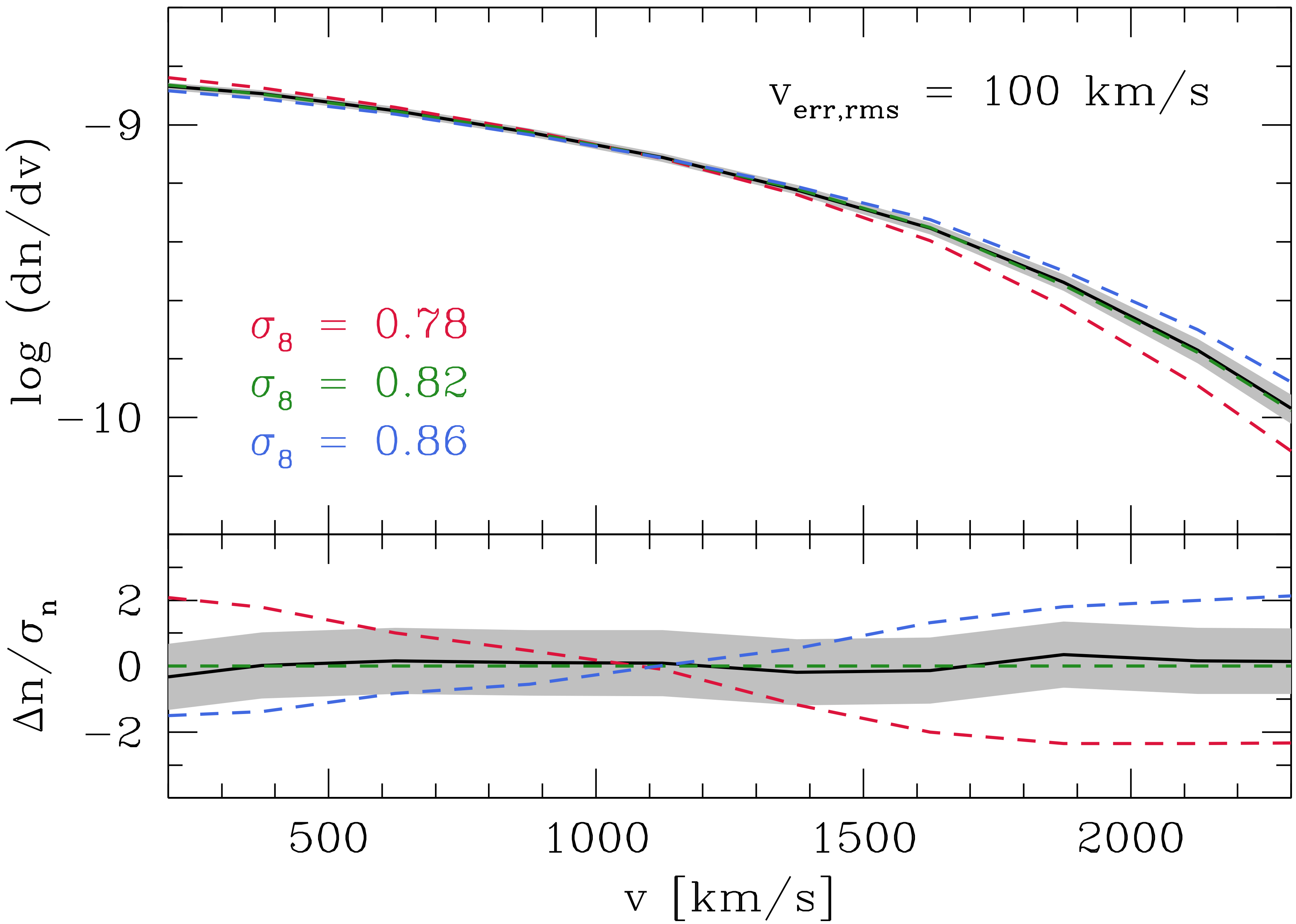
$$\frac{dn}{dv}(v) = \frac{1}{V}\sum_{i}^{N}[\mathrm{PDF}(|v|)]_i$$

COUNTING CLUSTERS BY VELOCITIES



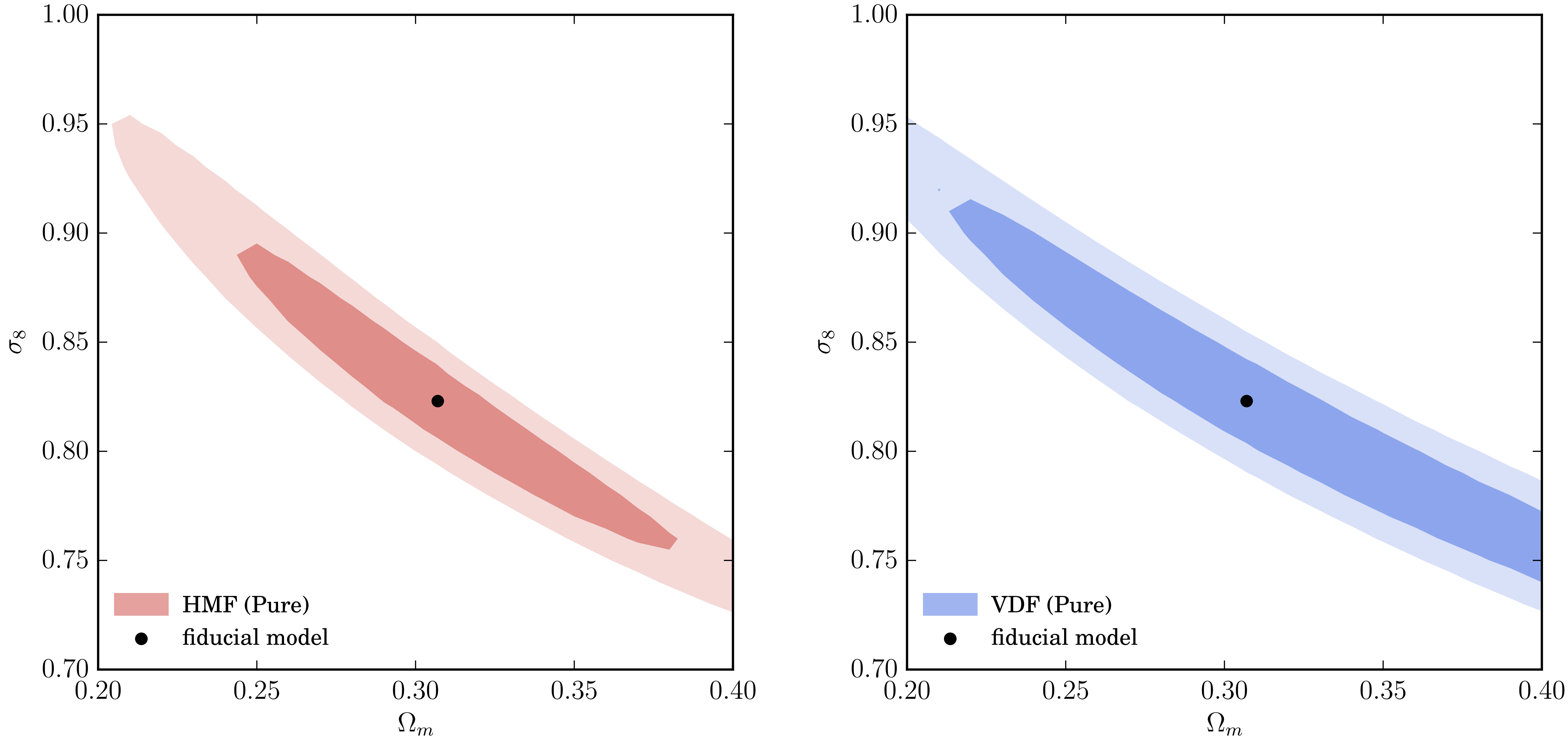
The velocity distribution function of galaxy clusters is constructed by summing the PDF(v) for N clusters in a known volume V.

COUNTING CLUSTERS BY VELOCITIES



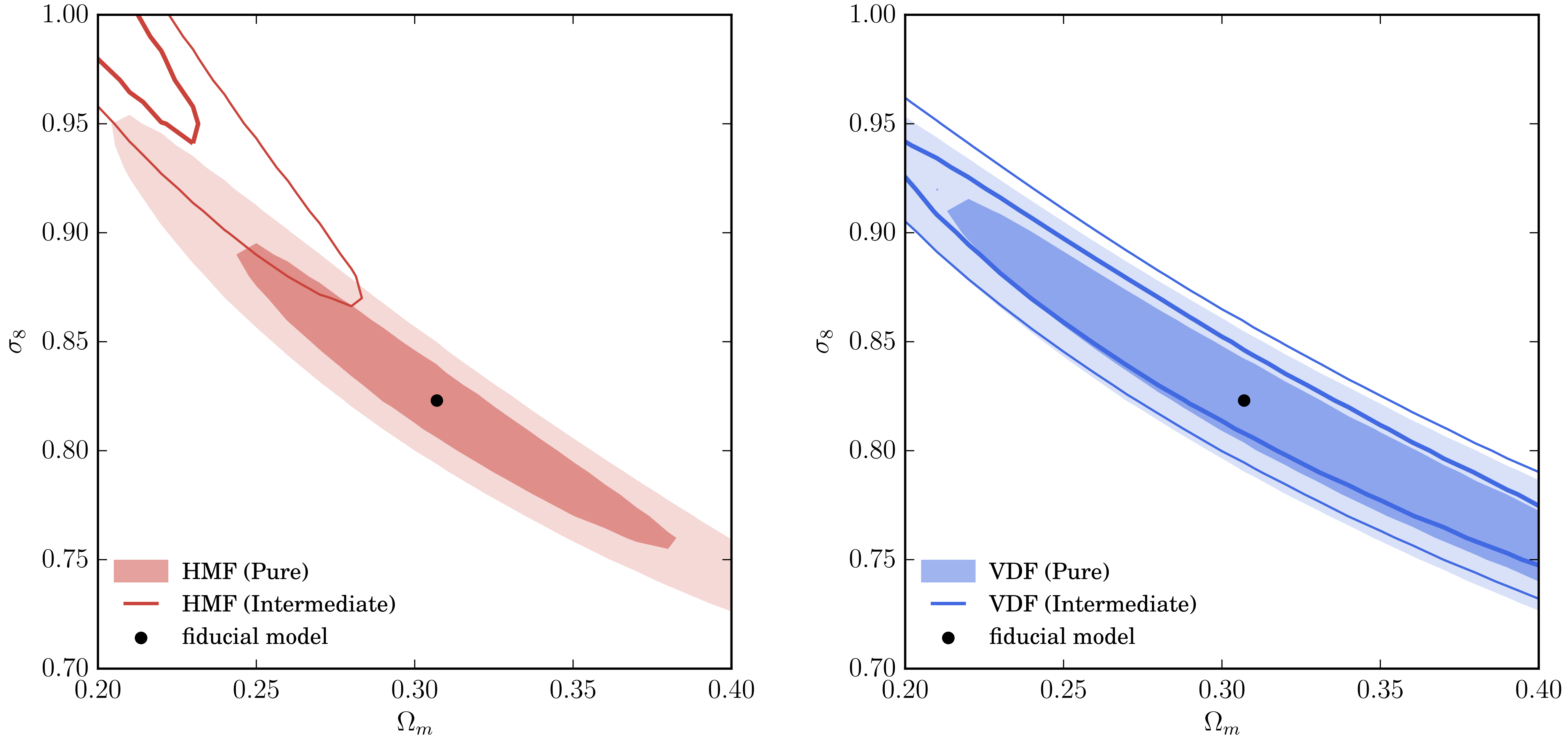
The velocity distribution function can be measured more accurately than the halo mass function with dynamical masses.

COSMOLOGICAL PARAMETERS



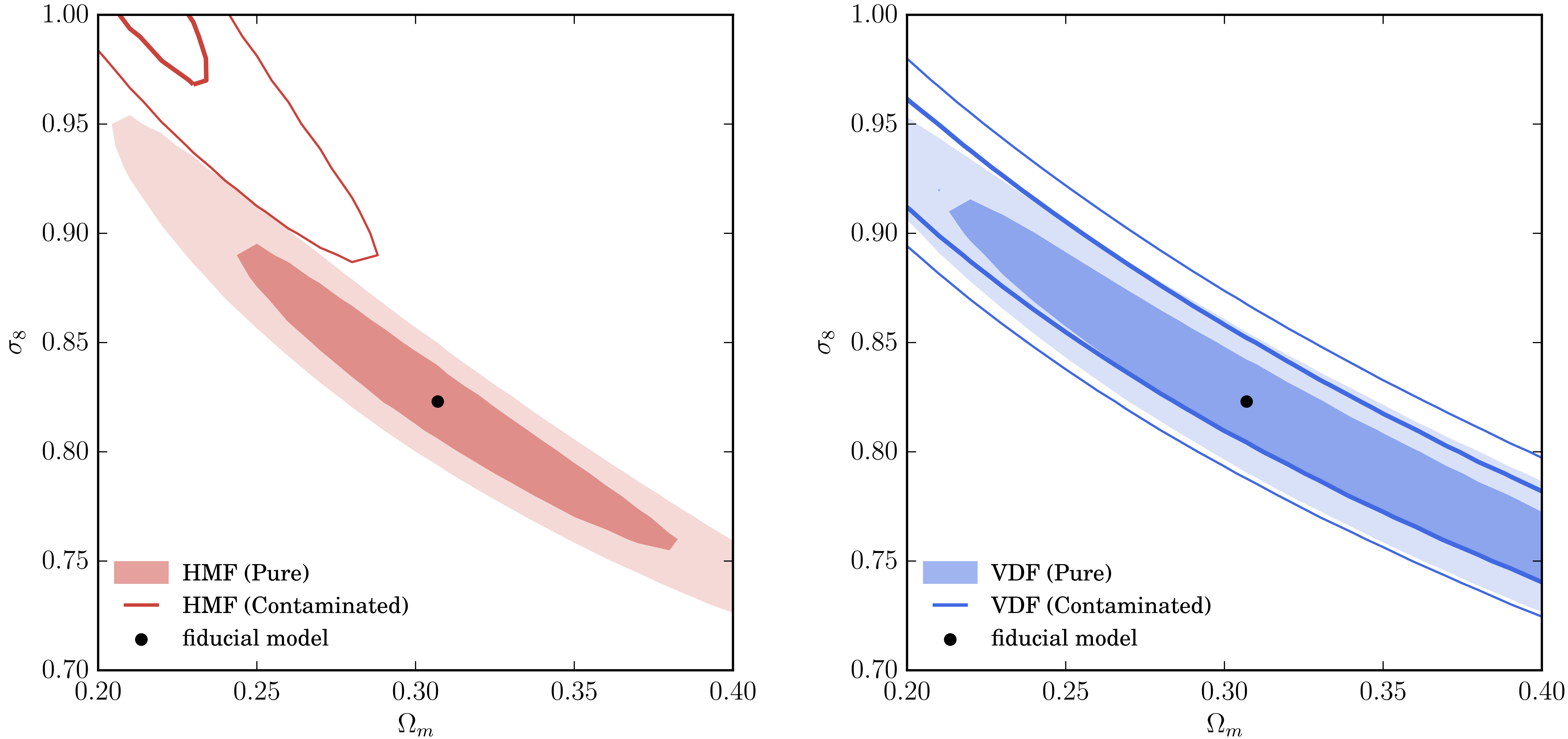
Idealistic analysis using spherical catalogs with true masses and velocities

COSMOLOGICAL PARAMETERS



Simple analysis using spherical catalogs with measurement errors

COSMOLOGICAL PARAMETERS



The VDF constrains the parameter combination: $\sigma_8 \Omega_{\mathrm{m}}^{0.29} = 0.589 \pm 0.014$

CONCLUDING THOUGHTS

What spectroscopic observations can be used to measure the VDF?

- HeCS-SZ by Rines et al (2015)
- Followup observations of optical clusters from e.g. DES, HSC
- Followup observations of SZ clusters from e.g. AdvACT, SPT-3G

What is the distribution of observables for other mass proxies?

- Lensing: PDF of smoothed shear/convergence (see also Liu et al. 2015)
- SZ: PDF of temperature distortions (see also Hill et al. 2014)
- X-ray: PDF derived from mass profiles